IN THE UNITED STATES DISTRICT COURT
FOR THE EASTERN DISTRICT OF TEXAS
MARSHALL DIVISION

STORMEDIA TEXAS, LLC,

Plaintiff,

vs.

COMPUSA, INC., a Delaware corporation; FUJITSU COMPUTER PRODUCTS OF AMERICA, INC , a California corporation; FUJITSU COMPUTER SYSTEMS CORPORATION, a California corporation; HITACHI GLOBAL STORAGE TECHNOLOGIES, INC., a Delaware corporation; J & R ELECTRONICS, INC., a New York corporation; SAMSUNG SEMICONDUCTOR, INC., a California corporation; SEAGATE TECHNOLOGY, a Cayman Islands corporation; SEAGATE TECHNOLOGY LLC; a Delaware limited liability company; TIGERDIRECT, INC. a Florida corporation; TOSHIBA AMERICA INFORMATION SYSTEMS, INC., a California corporation; and WESTERN DIGITAL TECHNOLOGIES, INC., a Delaware corporation,

Defendants.

CASE NO. 2-07CV-025 TJW

Jury Trial Demanded

COMPLAINT FOR PATENT INFRINGEMENT

StorMedia Texas, LLC ("StorMedia Texas") sues Defendants CompUSA, Inc., Fujitsu Computer Products of America, Inc., Fujitsu Computer Systems Corporation, Hitachi Global Storage Technologies, Inc., J & R Electronics, Inc., Samsung Semiconductor, Inc., Seagate Technology, Seagate Technology, LLC, TigerDirect, Inc., Toshiba America Information

Systems, Inc., and Western Digital Technologies, Inc , (collectively "Defendants") and, on information and belief, alleges as follows:

Introduction

1. Plaintiff StorMedia Texas owns the invention described and claimed in United States Patent No 6,805,891 entitled "Recording media having protective overcoats of highly tetrahedral amorphous carbon and methods for their production" (the "'891 patent"). Defendants (a) have used, and continue to use, Plaintiff's patented technology in products that they make, use, import, sell, and offer to sell, without Plaintiff's permission; and (b) have contributed to or induced, and continue to contribute to or induce, others to infringe the '891 patent. Plaintiff StorMedia Texas seeks damages for patent infringement and an injunction preventing Defendants from making, using, selling, or offering to sell, and from contributing to and inducing others to make, use, sell, or offer to sell, the technology claimed by the '891 patent without Plaintiff's permission.

Jurisdiction and Venue

2. This is an action for patent infringement arising under the patent laws of the United States, 35 U.S.C. §§ 271 and 281, *et seq*. The Court has original jurisdiction over this patent infringement action under 28 U.S.C. § 1338(a)

3. Within this judicial district each of the Defendants has committed acts and continues to commit acts that give rise to this action, including making sales of infringing products and offering infringing products for sale. Venue is proper in this district pursuant to 28 U.S.C. § 1391(b) and § 1400.

Plaintiff StorMedia Texas

4. Plaintiff StorMedia Texas, LLC is a limited liability company existing under, and by virtue of, the laws of the State of Texas.

Defendants

5. Defendant CompUSA, Inc. ("CompUSA") is a corporation organized and existing under the laws of the State of Delaware, with its principal place of business in Dallas, Texas.

6. Defendant Fujitsu Computer Products of America, Inc. ("Fujitsu Computer Products") is a corporation organized and existing under the laws of the State of California, with its principal place of business in Sunnyvale, California. Fujitsu Computer Products is registered to do business as a foreign for-profit corporation in the state of Texas. Fujitsu Computer Product's foreign corporation registration lists CT Corporation System as its registered agent for service of process.

7. Defendant Fujitsu Computer Systems Corporation ("Fujitsu Computer Systems") is a corporation organized and existing under the laws of the State of California, with its principal place of business in Sunnyvale, California. Fujitsu Computer Systems is registered to do business as a foreign for-profit corporation in the state of Texas. Fujitsu Computer System's foreign corporation registration lists Corporation Service Company DBA CSC-Lawyers Incorporating Service Company as its registered agent for service of process.

8. Defendant Hitachi Global Storage Technologies, Inc. ("Hitachi") is a corporation organized and existing under the laws of the State of Delaware, with its principal place of business in San Jose, California. Hitachi is registered to do business as a foreign for-profit corporation in the state of Texas. Hitachi's foreign corporation registration lists CT Corporation System as its registered agent for service of process.

9. Defendant J & R Electronics, Inc ("J & R Electronics") is a corporation organized and existing under the laws of the State of New York, with its principle place of business in New York, New York.

10. Defendant Samsung Semiconductor, Inc. ("Samsung") is a corporation organized and existing under the laws of the State of California, with its principal place of business in San Jose, California. Samsung is registered to do business as a foreign corporation in the state of Texas. Samsung's foreign corporation registration lists National Registered Agents, Inc. as its registered agent for service of process

11. Defendant Seagate Technology ("Seagate Technology") is a corporation organized and existing under the laws of the Cayman Islands, with its principal place of business in George Town, Grand Cayman, Cayman Islands.

12. Defendant Seagate Technology, LLC ("Seagate LLC") is a limited liability company organized and existing under the laws of the State of Delaware, with its principal place of business in Scotts Valley, California. Seagate LLC is registered to do business as a foreign limited liability company in the state of Texas. Seagate LLC's foreign corporation registration lists CT Corporation System as its registered agent for service of process

13. Defendant TigerDirect, Inc. ("TigerDirect") is a corporation organized and existing under the laws of the State of Florida, with its principle place of business in Miami, Florida.

14. Defendant Toshiba America Information Systems, Inc. ("Toshiba") is a corporation organized and existing under the laws of the State of California, with its principal place of business in Irvine, California. Toshiba is registered to do business as a foreign for-profit corporation in the state of Texas. Toshiba's foreign corporation registration lists CT Corporation System as its registered agent for service of process.

15. Defendant Western Digital Technologies, Inc. ("Western Digital") is a corporation organized and existing under the laws of the State of Delaware, with its principal place of business in Lake Forest, California. Western Digital is registered to do business as a foreign for-profit corporation in the state of Texas. Western Digital's foreign corporation registration lists National Registered Agents, Inc. as its registered agent for service of process.

First Claim for Patent Infringement
(infringement of the '891 patent)

16. Plaintiff incorporates by reference each of the allegations in paragraphs 1 - 15 above and further alleges as follows:

17. The United States Patent and Trademark Office issued the '891 patent on October 19, 2004. Attached as Exhibit A is what is believed to be a copy of the text of the '891 patent. Through assignment, Plaintiff is the owner of all right, title, and interest in the '891 patent, including all rights to pursue and collect damages for past infringements of the patent.

18. Defendants have infringed, contributed to the infringement, and induced others to infringe the '891 patent and, unless enjoined, will continue to do so, by manufacturing, importing, using, selling, or offering for sale products, in particular hard disk drives, that infringe the claims of the '891 patent and by contributing to or inducing others to infringe the claims of the '891 patent without a license or permission from Plaintiff.

19. Plaintiff has been damaged by Defendants' infringement of the '891 patent and will suffer additional irreparable damage and impairment of the value of its patent rights unless Defendants are enjoined from continuing to infringe the '891 patent.

20. The Defendants are and have been willfully infringing one or more claims of the '891 patent.

21. Plaintiff is entitled to recover damages from the Defendants to compensate for the infringement.

22. Plaintiff demands trial by jury of all issues relating to this claim.

WHEREFORE, Plaintiff prays for judgment as follows:

A. A decree preliminarily and permanently enjoining Defendants, their officers, directors, employees, agents, and all persons in active concert with them, from infringing, and contributing to or inducing others to infringe, the '891 patent;

B. Compensatory damages for Defendants' infringement of the '891 patent;

C. Treble the compensatory damages as consequence of Defendants' willful infringement;

D Costs of suit and attorneys' fees on the basis that this patent infringement case is exceptional;

E. Pre-judgment interest; and

F. For such other relief as justice requires.

Dated: January 22, 2006

Respectfully submitted,

By: S Calvin Capshaw (by permission ETO)

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US006805891B2

(12) **United States Patent**
Vijayen et al.

(10) **Patent No.: US 6,805,891 B2**
(45) **Date of Patent: Oct. 19, 2004**

(54) **RECORDING MEDIA HAVING PROTECTIVE OVERCOATS OF HIGHLY TETRAHEDRAL AMORPHOUS CARBON AND METHODS FOR THEIR PRODUCTION**

(75) Inventors: **Veerasamy Vijayen**, San Jose, CA (US); **Manfred Weiler**, Elbersdorf (DE); **Eric Li** Palo Alto, CA (US)

(73) Assignee: **United Mobile Corporation** Los Altos, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days

(21) Appl. No.: **10/350,498**

(22) Filed: **Jan. 23, 2003**

(65) **Prior Publication Data**

US 2003/0148103 A1 Aug. 7, 2003

Related U.S. Application Data

(62) Division of application No. 09/165,513, filed on Oct. 2, 1998, now Pat. No. 6,537,668, which is a division of application No. 08/761,336 filed on Dec. 10, 1996, now Pat. No. 5,858,477

(60) Provisional application No. 60/018,746, filed on May 31, 1996, and provisional application No. 60/018,793, filed on May 31, 1996

(51) **Int. Cl.**[7] **G11B 5/72**

(52) U.S. Cl. ..... 426/336; 428/408; 428/694 TC

(58) Field of Search ..... 428/408, 694 TC, 428/336

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,123,316	A	10/1978	Tsuchimoto
4,226,666	A	10/1980	Winters et al.
4,749,608	A	6/1988	Nakayama et al.
4,822,466	A	4/1989	Rabalais et al.
5,017,835	A	5/1991	Occhiuto

(List continued on next page.)

FOREIGN PATENT DOCUMENTS

EP	0 522 491 A1	7/1993
EP	0 595 564 A2	5/1994
EP	0 700 033 A2	3/1996
JP	02168540	6/1990
JP	5-143971	6/1993
JP	6-139560	5/1994
JP	06349054	12/1994

OTHER PUBLICATIONS

Aisenberg, S. et al., "Ion-Beam Deposition of Thin Films of Diamondlike Carbon," *J. Appl. Phys.*, vol. 42, No. 7, Jun. 1971, pp. 2953–2958

(List continued on next page.)

Primary Examiner—Stevan A. Resan
(74) *Attorney, Agent, or Firm*—Townsend and Townsend and Crew LLP

(57) **ABSTRACT**

The invention provides systems and methods for the deposition of an improved diamond-like carbon material, particularly for the production of magnetic recording media. The diamond-like carbon material of the present invention is highly tetrahedral, that is, it features a large number of the sp^3 carbon—carbon bonds which are found within a diamond crystal lattice. The material is also amorphous, providing a combination of short-range order with long-range disorder, and can be deposited as films which are ultrasmooth and continuous at thicknesses substantially lower than known amorphous carbon coating materials. The carbon protective coatings of the present invention will often be hydrogenated. In a preferred method for depositing of these materials, capacitive coupling forms a highly uniform, selectively energized stream of ions from a dense, inductively ionized plasma. Such inductive ionization is enhanced by a relatively slow moving (or "quasi-static") magnetic field, which promotes resonant ionization and ion beam homogenization.

14 Claims, 12 Drawing Sheets

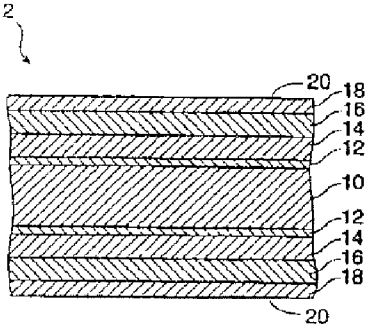

Exhibit A

U.S. PATENT DOCUMENTS

5,064,809	A	11/1991	Hed
5,082,359	A	1/1992	Kirkpatrick
5,082,522	A	1/1992	Purdes et al
5,091,049	A	2/1992	Campbell et al
5,126,206	A	6/1992	Garg et al
5,156,703	A	10/1992	Oechsner
5,182,132	A	1/1993	Murai et al
5,186,973	A	2/1993	Garg et al
5,246,884	A	9/1993	Jaso et al.
5,364,690	A	11/1994	Takahashi et al
5,374,318	A	12/1994	Rabalais et al
5,411,797	A	5/1995	Davanloo et al
5,423,915	A	6/1995	Murata et al
5,462,781	A	10/1995	Grill et al
5,466,431	A	11/1995	Dorfman et al
5,470,661	A	11/1995	Bailey et al
5,559,367	A	9/1996	Cohen et al.
5,569,501	A	10/1996	Bailey et al.
5,607,783	A	3/1997	Onodera
5,616,179	A	4/1997	Baldwin et al
5,637,393	A	6/1997	Ueda et al
5,705,272	A	1/1998	Taniguchi
5,852,303	A	12/1998	Cuomo et al
5,945,191	A	8/1999	Hwang et al
6,064,148	A	5/2000	Folt et al
6,194,047	B1	2/2001	Hayashi

OTHER PUBLICATIONS

Boxman, R.L. et al., "Recent Progress in Filtered Vacuum Arc Deposition," *Paper submitted Int. Conf. Metallurgical Coatings and Thin Films, San Diego, Apr. 1996.*

Chowalla, M. et al., "Deposition of Smooth Tetrahedral Amorpheus Carbon Thin Films Using a Cathodic Arc Without a Macroparticle Filter," *Appl. Phys. Lett.*, vol. 67, No. 7, pp. 894–896, 1995.

Chhowalla, M. et al., "Stationary Carbon Cathodic Arc: Plasma and Film Characterization," *J. Appl. Phys.* vol. 79, No. 5, pp. 2237–2244, 1996.

Fuchs, Armin, Thesis (1987)

Grill, A., et al., "Diamondlike Carbon Films by rf Plasma–Assisted Chemical Vapor Deposition from Acetylene," *IBM J. Res. Develop.*, vol. 34, No. 6, Nov. 1990, pp. 849–857.

Grill, A., et al., "Diamondlike Carbon Deposited by DC PACVD," *Diamond Films and Techn.*, vol. 1, No. 4 (1992), pp. 219–233.

Kuhn, M., et al., "Deposition of Carbon Films By A Filtered Cathodic Arc," *Diamond and Related Materials*, vol. 2, No. 10, Aug. 1993, pp. 1350–1354.

Martin, Dieter, Dissertation (1995)

Oeschner, H. "Electron Cyclotron Wave Resonances and Power Absorption Effects in Electrodeless Low Pressure H.F. Plasmas with a Superimposed Static Magnetic Field," *Plasma Physics*, vol. 16, pp. 835–844, 1974.

Oeschner, H., et al. "An RF Plasma Beam Source for Thin Film and Surface Technology," *Proc. 1st Int. Conf. on Plasma Surface Engineering, Garmisch Partenkirchen*, 1988, vol. II, DGM Informationen Gesellschaft Obvurocl, pp. 1017–1024, 1989.

Park, K.D. et al., "Enhancement of Field–Emission Characteristics by Using Hydrogen–Free Diamond–Like Carbon Film Deposited by Plasma–Enhanced Chemical Vapor Deposition" (1996) *SID 96 Digest* pp. 49–52.

Pfeiffer, B., "Skin Effect in Anisotropic Plasmas and Resonance Excitation of Electron–CyClotron Waves I. Theory," *Journal of Applied Physics* vol. 37, No. 4, pp. 1624–1627, 1966.

Sager, O. "The influence of Nonuniform Density Distribution and Electron Temperature on the Helicon–Resonances in Low Pressure Discharges." 1971

Schön, Franz, Thesis (1968)

Szuszczewicz, Edward P. "Spatial Distributions of Plasma Density in a High–Frequency Discharge with a Superimposed Static Magnetic Field," *The Physics of Fluids*, vol. 15, No. 12, pp. 2240–2246, 1972.

Veerasamy, V.S. et al. "Electronic Density of States in Highly Tetrahedral Amorphous Carbon," *Solid–State Electronics*, vol. 37, No. 2, pp. 319–326, 1994.

Veerasamy, V.S. Dissertation (1994)

Weiler, M. et al. "Preparation and Properties of Highly Tetrahedral Hydrogenated Amorphous Carbon," *Physical Review B*, vol. 53, No. 3, pp. 245–253, 1994.

Weiler, M. et al. "Highly Tetrahedral, Diamond–like Amorphous Hydrogenated Carbon Prepared from a Plasma Beam Source," *Appl. Phys. Lett.*, vol. 64, No. 23, pp. 2797–2799.

Weiler, Manfred, Thesis (1989)

Weiler, Manfred, Dissertation (1994)

PR Newswire, *CeBIT Showcase for Major Advance in Magnetic Disk Storage Capacity*, Feb. 2000, Hanover, Germany, website: http://www.prnewswire.com (Feb. 19, 2000).

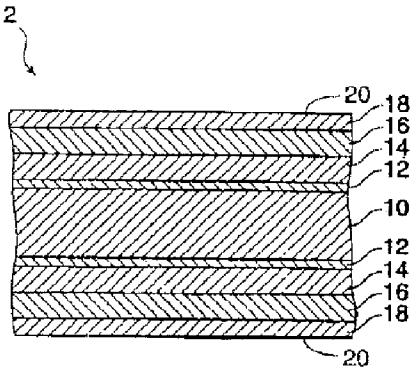
2
20
18
16
14
12
10
12
14
16
18
20

FIG. 1

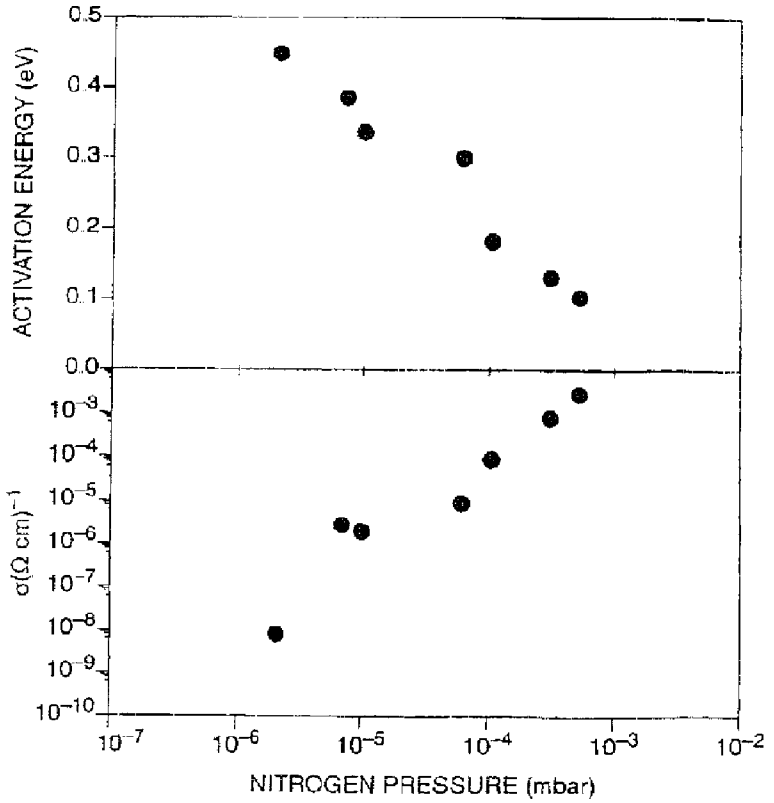
ACTIVATION ENERGY (eV)
0.5
0.4
0.3
0.2
0.1
0.0
σ(Ω cm)⁻¹
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻⁷
10⁻⁶
10⁻⁵
10⁻⁴
10⁻³
10⁻²
NITROGEN PRESSURE (mbar)

FIG. 1A

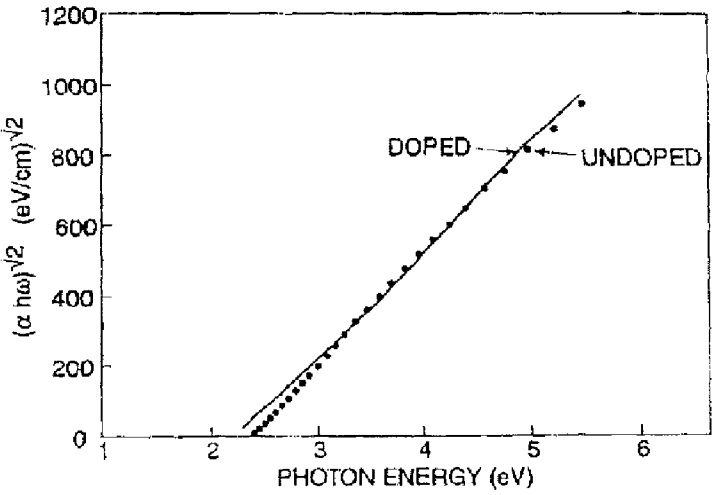
1200
1000
800
600
400
200
0
$(\alpha\ h\omega)^{1/2}$ $(eV/cm)^{1/2}$
DOPED
UNDOPED
1
2
3
4
5
6
PHOTON ENERGY (eV)

FIG. 1B

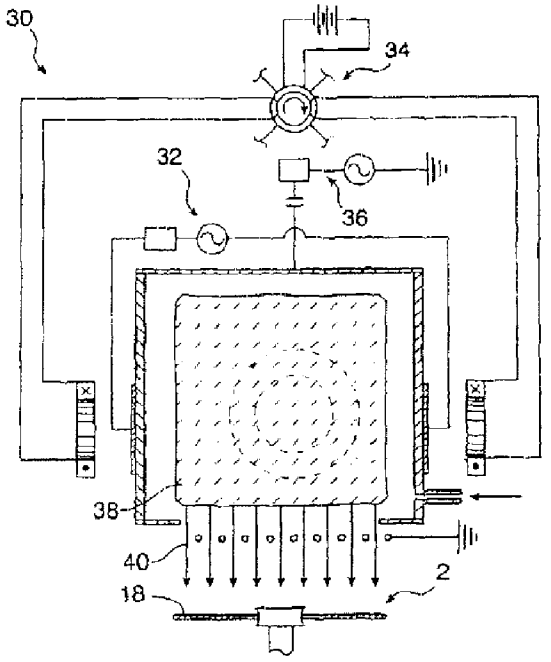
30
34
32
36
38
40
18
2

FIG. 2

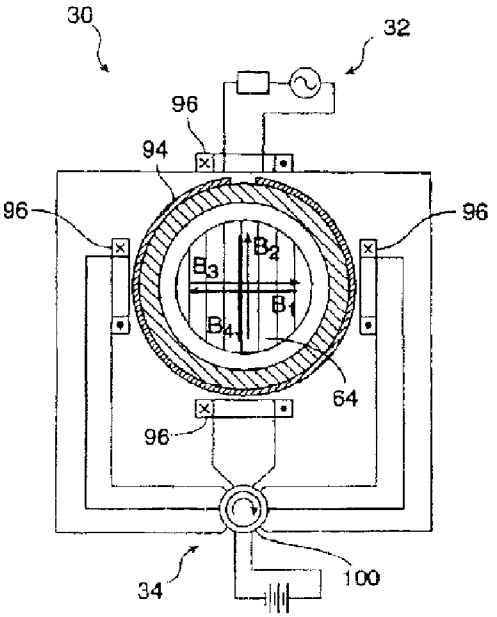
30
32
96
94
96
96
B_3
B_2
B_1
B_4
64
96
34
100

FIG. 2A

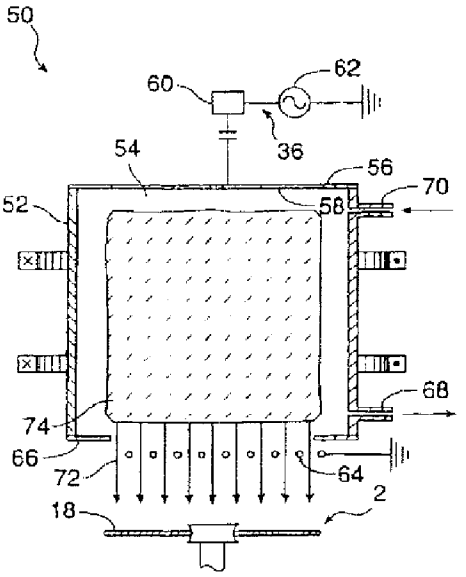
50
60
62
36
54
56
70
52
58
68
74
66
72
64
18
2

FIG. 3A

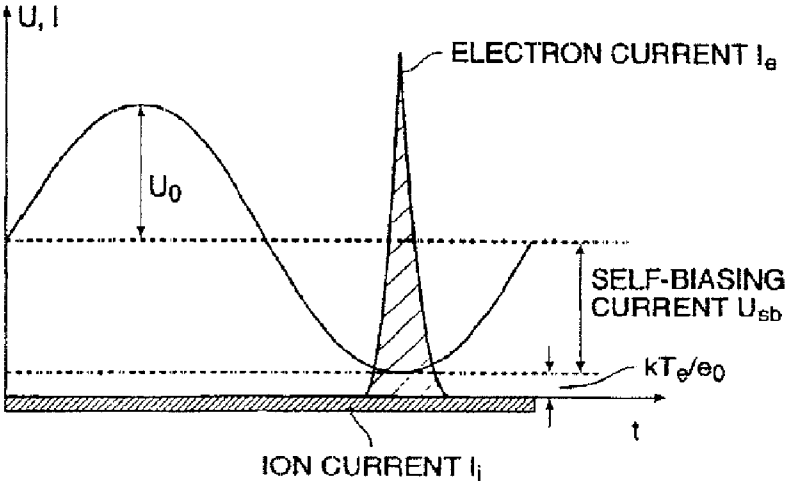
U, I
ELECTRON CURRENT I_e
U_0
SELF-BIASING CURRENT U_{sb}
kT_e/e_0
t
ION CURRENT I_i

FIG. 3B

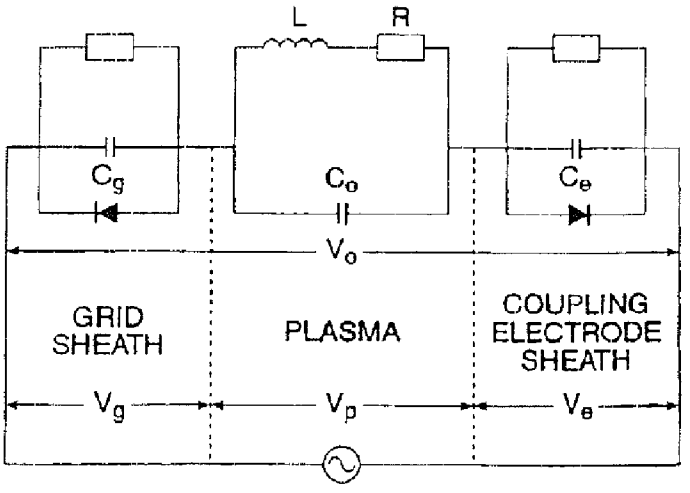
L
R
C_g
C_o
C_e
V_o
GRID SHEATH
PLASMA
COUPLING ELECTRODE SHEATH
V_g
V_p
V_e

FIG. 3C

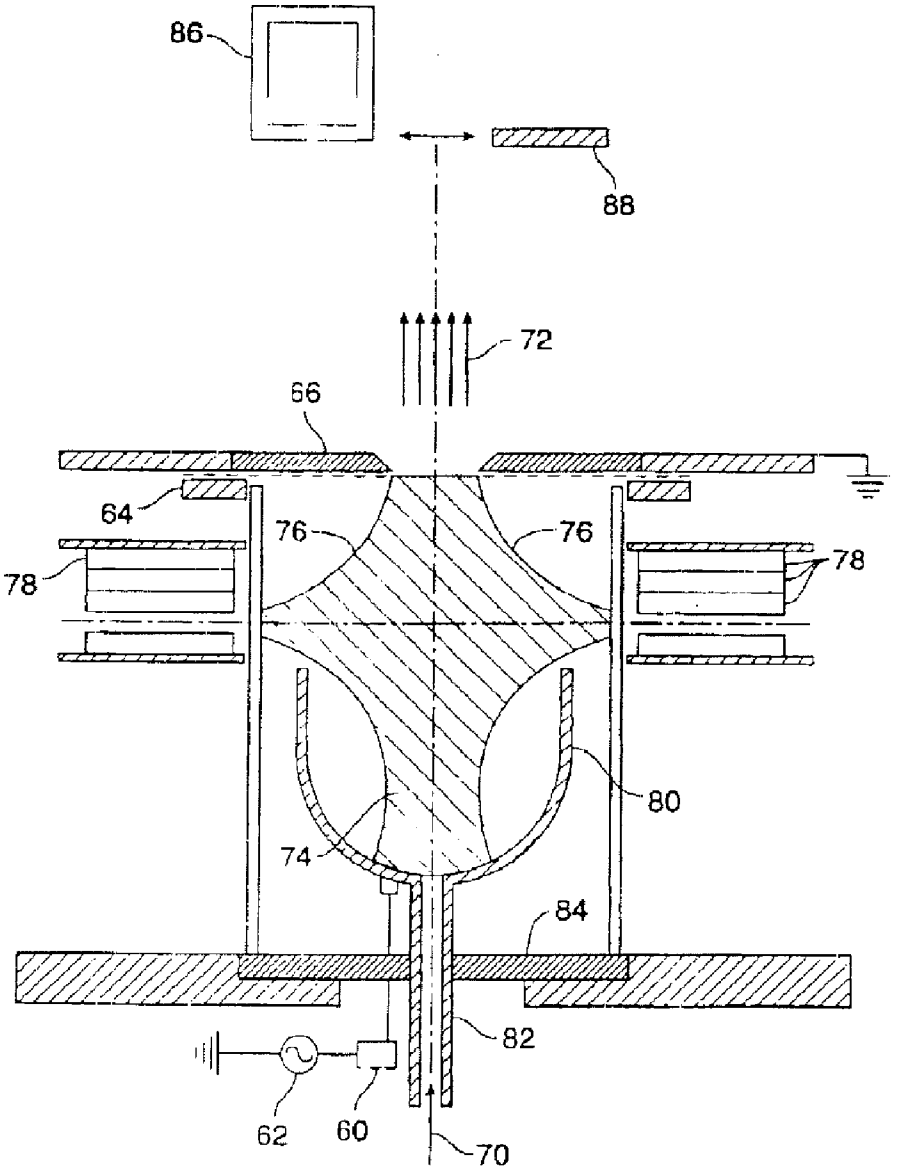

FIG. 3D

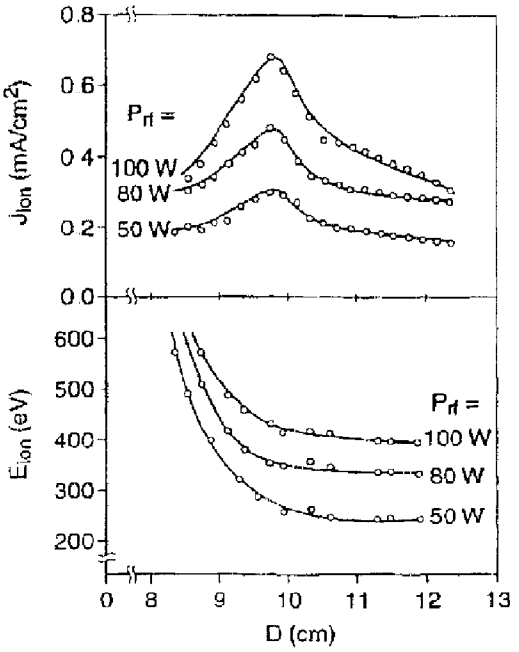
0.8
0.6
0.4
0.2
0.0
J_{ion} (mA/cm^2)
P_{rf} =
100 W
80 W
50 W
600
500
400
300
200
E_{ion} (eV)
P_{rf} =
100 W
80 W
50 W
0 8 9 10 11 12 13
D (cm)

FIG. 3E

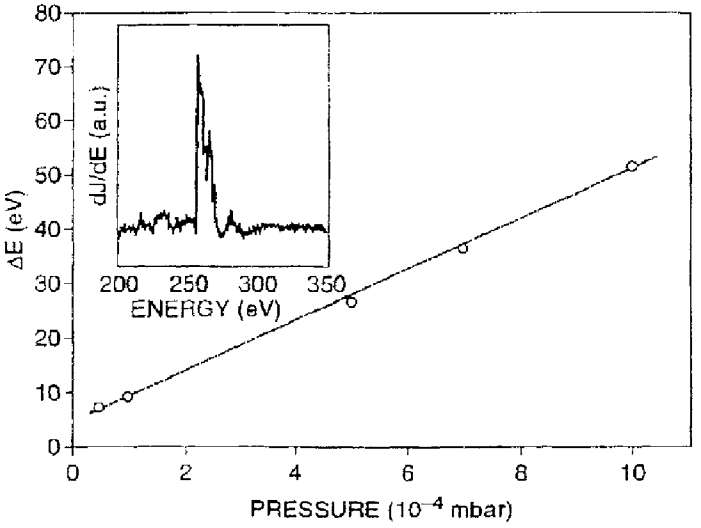
80
70
60
50
40
30
20
10
0
ΔE (eV)
dJ/dE (a.u.)
200 250 300 350
ENERGY (eV)
0 2 4 6 8 10
PRESSURE (10^{-4} mbar)

FIG. 3F

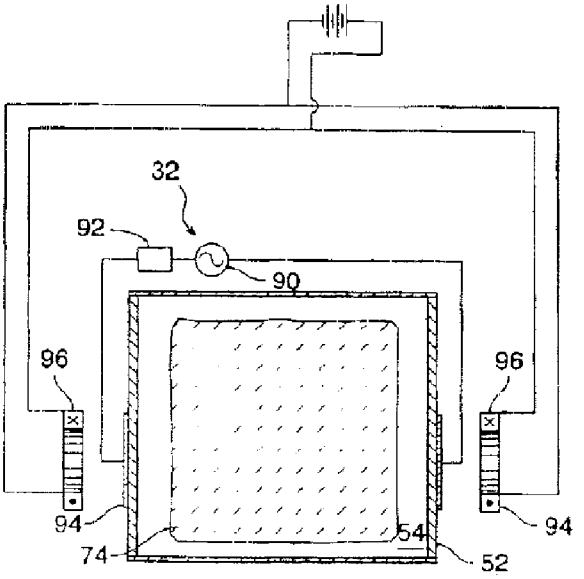

FIG. 4A
PRIOR ART

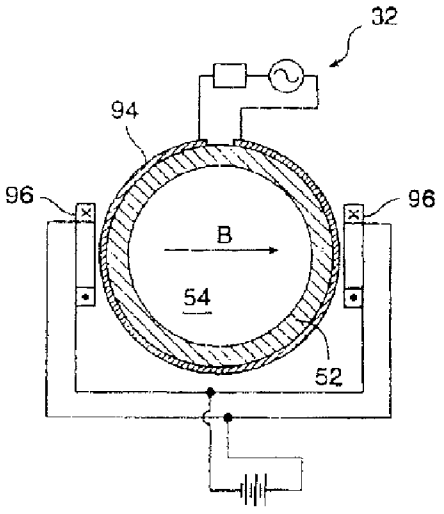

FIG. 4B
PRIOR ART

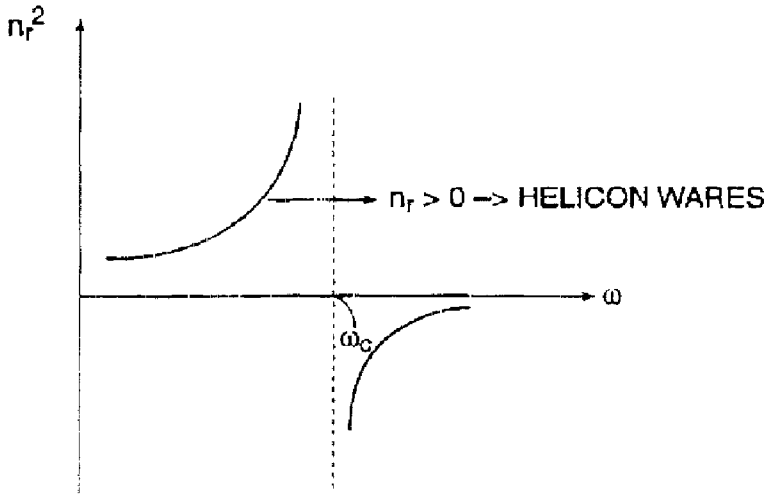
n_r^2
$n_r > 0$ –> HELICON WARES
ω
ω_c

FIG. 4C

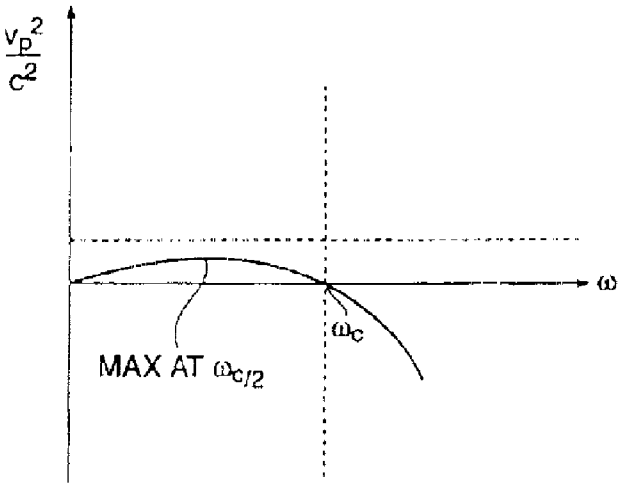
$\frac{v_p^2}{c^2}$
ω
ω_c
MAX AT $\omega_{c/2}$

FIG. 4D

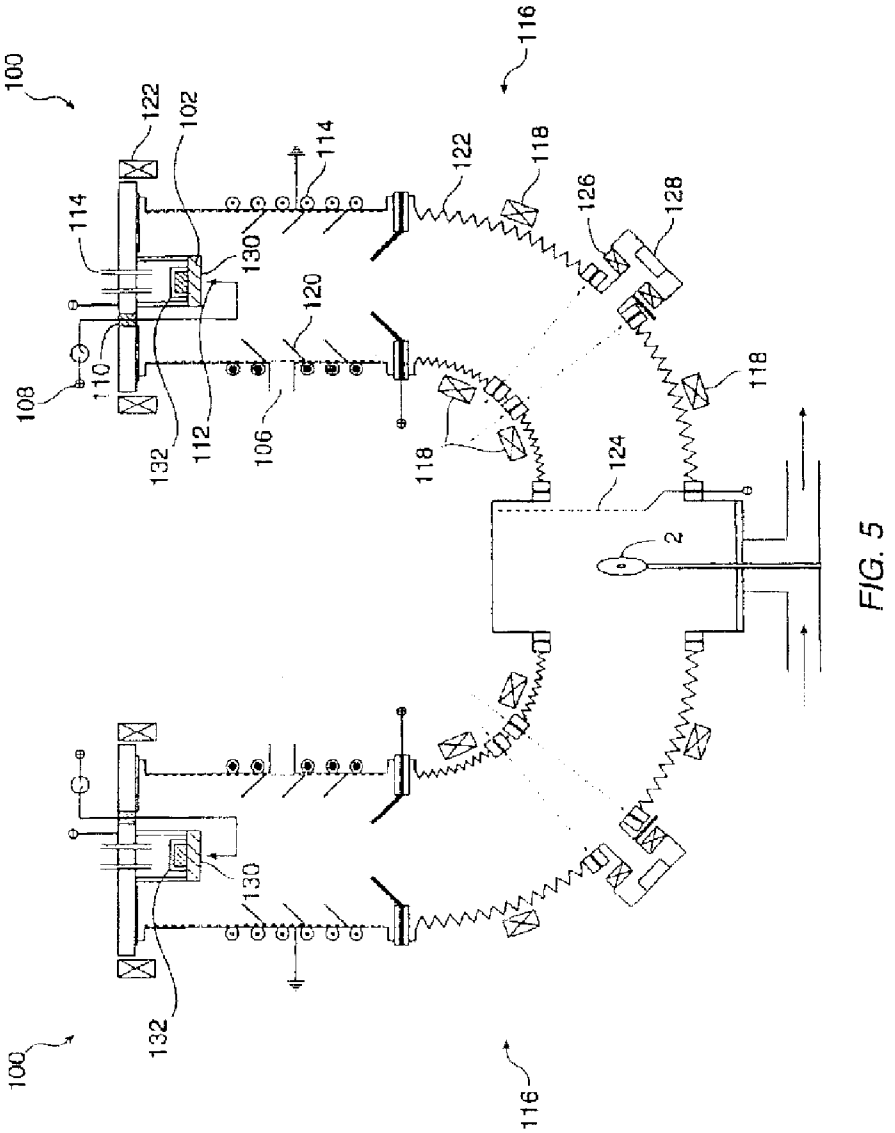
100
116
122
102
114
122
118
126
128
114
130
120
108
110
118
132
112
106
118
124
118
2
130
132
100
116

FIG. 5

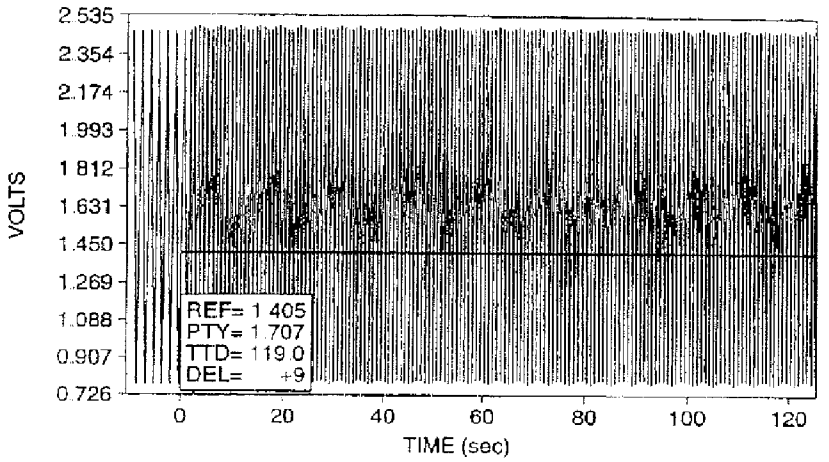
2.535
2.354
2.174
1.993
1.812
1.631
1.450
1.269
1.088
0.907
0.726
VOLTS
REF= 1.405
PTY= 1.707
TTD= 119.0
DEL= +9
0
20
40
60
80
100
120
TIME (sec)

FIG. 6A

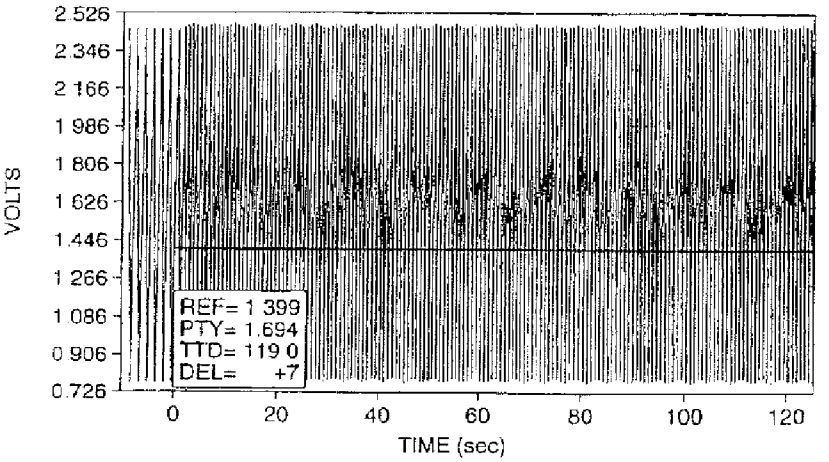
2.526
2.346
2.166
1.986
1.806
1.626
1.446
1.266
1.086
0.906
0.726
VOLTS
REF= 1.399
PTY= 1.694
TTD= 119.0
DEL= +7
0
20
40
60
80
100
120
TIME (sec)

FIG. 6B

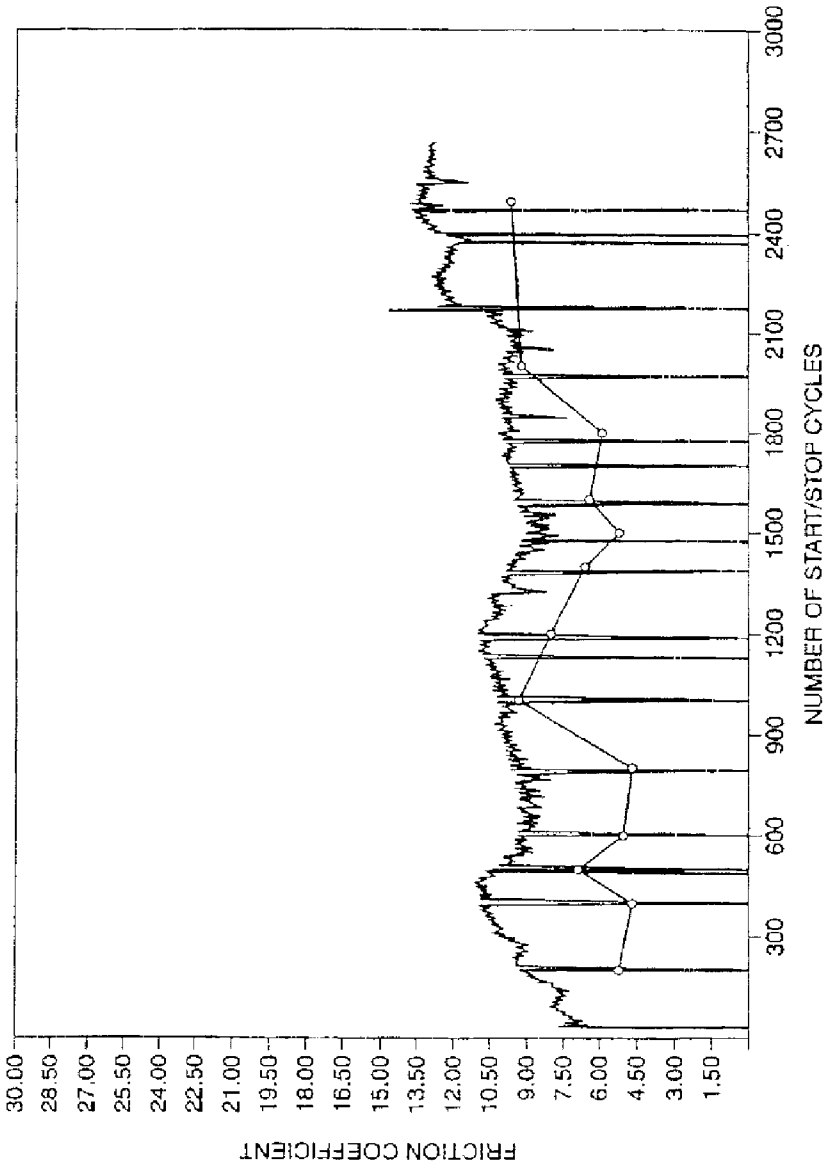
FRICTION COEFFICIENT
30.00
28.50
27.00
25.50
24.00
22.50
21.00
19.50
18.00
16.50
15.00
13.50
12.00
10.50
9.00
7.50
6.00
4.50
3.00
1.50
NUMBER OF START/STOP CYCLES
300
600
900
1200
1500
1800
2100
2400
2700
3000

FIG. 7

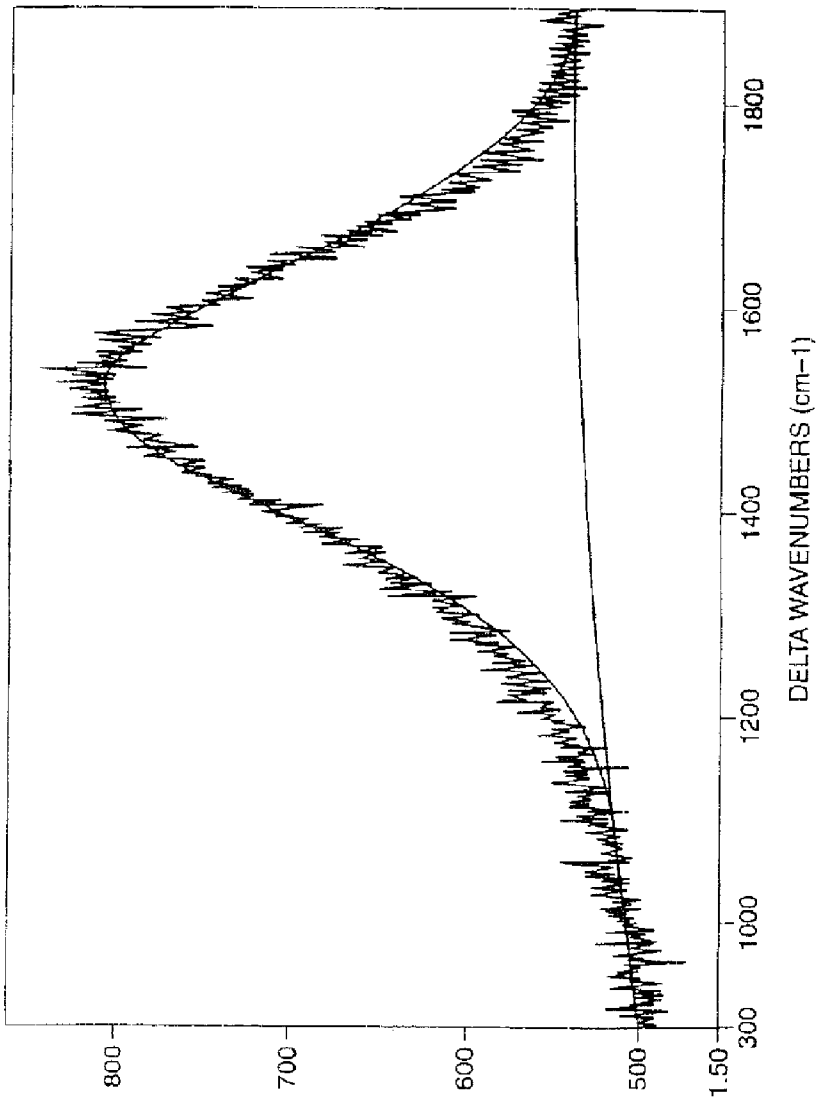
800
700
600
500
1.50
300
1000
1200
1400
1600
1800
DELTA WAVENUMBERS (cm-1)

FIG. 8

RECORDING MEDIA HAVING PROTECTIVE OVERCOATS OF HIGHLY TETRAHEDRAL AMORPHOUS CARBON AND METHODS FOR THEIR PRODUCTION

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a divisional of and claims the benefit of priority from U.S. patent application Ser. No. 09/165,513, filed Oct. 2, 1998, which is a divisional of U.S. patent application Ser. No. 08/761,336 now U.S. Pat. No. 5,858,477 filed Dec. 10, 1996, which is a continuation-in-part of and claims priority from U.S. Provisional Patent Applications Serial No. 60/018,793, filed May 31, 1996, and Serial No. 60/018,746, filed May 31, 1996, the full disclosures of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to thin films and methods for their deposition, and more particularly, provides diamond-like films, plasma beam deposition systems, and methods useful for production of diamond-like protective overcoats on magnetic recording media and other industrial applications.

In recent years, there has been considerable interest in the deposition of a group of materials referred to as diamond-like carbon. Diamond-like carbon can generally be defined as a metastable, high density form of amorphous carbon. Diamond-like carbon is valued for its high mechanical hardness, low friction, optical transparency, and chemical inertness.

Deposition of diamond-like carbon films often involves chemical vapor deposition techniques, the deposition processes often being plasma enhanced. Known diamond-like films often include carbon with hydrogen, fluorine, or some other agent. The durability and advantageous electrical properties of diamond-like carbon films have led to numerous proposals to apply these films to semiconductors, optics, and a wide variety of other industrial uses. Unfortunately, the cost and complexity of providing these advantageous diamond-like carbon films using known chemical vapor deposition processes has somewhat limited their use. Furthermore, while a wide variety of diamond-like carbon coating films have been deposited in laboratories, many of these films have been found to have less than ideal material characteristics.

A very different form of amorphous carbon is generally applied as a protective overcoat for magnetic recording media. Magnetic recording disks generally comprise a substrate having a magnetic layer and a number of underlayers and overlayers deposited thereon. The nature and composition of each layer is selected to provide the desired magnetic recording characteristics, as is generally recognized in the industry.

The information stored in magnetic recording media generally comprises variations in the magnetic field of a thin film of ferromagnetic material, such as a magnetic oxide or magnetic alloy. Usually, a protective layer is formed over the top of the magnetic layer, and a layer of lubricating material is deposited over the protective layer. These protective and lubricating layers combine to increase the reliability and durability of the magnetic recording media by limiting friction and erosion of the magnetic recording layer. Sputtered amorphous carbon films have gained widespread usage as protective overcoats for rigid magnetic recording disks.

Sputtered amorphous carbon overcoats have been shown to provide a high degree of wear protection with a relatively thin protective layer. Magnetic recording disk structures including sputtered amorphous carbon have been very successful and allow for quite high recording densities. As with all successes, however, it is presently desired to provide magnetic recording disks having even higher recording densities.

Recording densities can generally be improved by reducing the spacing between the recording transducer, called the read/write head, and the magnetic layer of the magnetic recording disk (or more specifically, between the read/write head and the middle of the magnetic layer). In modern magnetic recording systems, the read/write head often glides over the recording surface on an air bearing, a layer of air which moves with the rotating disk. To minimize frictional contact between the rotating disk and the read/write head, the disk's surface is generally rougher (and the glide height therefore higher) than would otherwise be ideal for high density magnetic recording. Even if this glide height is reduced (or eliminated), the read/write head will be separated from the recording layer by the protective amorphous carbon overcoat. This protective layer alone may, to provide the desired media life, limit the areal density of the media. Generally, overcoat layer thicknesses are dictated by durability and continuity limitations. Sputtered carbon frequently becomes discontinuous at thicknesses below about 50 Å. Thus, the durability requirements of rigid magnetic recording media generally dictate that the distance between the read/write head and the magnetic recording layer be maintained, even though this limits the areal density of the magnetic recording media.

It has previously been proposed to utilize known chemical vapor deposition techniques to deposit a variety of diamond-like carbon materials for use as protective coatings for flexible magnetic recording tapes and magnetic recording heads. Unfortunately, known methods for chemical vapor deposition of diamond-like materials, including plasma enhanced methods, generally subject the substrate to temperatures of over 500° C., which is deleterious for most magnetic disk substrates. Therefore, these known diamond-like carbon films do provide relatively good hardness and frictional properties, they have found little practical application within the field of rigid magnetic recording media, in which sputtered amorphous carbon protective overcoats are overwhelmingly dominant.

For these reasons, it would be beneficial to provide improved magnetic protective overcoats with improved read/write head frictional and glide characteristics (generally called stiction) for recording media. Preferably, such an improved overcoat will provide durability and reliability without having to resort to the density-limiting glide heights and or protective overcoat thickness of known rigid magnetic recording media and without subjecting the media substrates to excessive temperatures.

It would also be desirable to provide improved diamond-like carbon materials and methods for their deposition. It would be particularly desirable if such materials and methods could be utilized for practical rigid magnetic recording media with reduced spacing between the read/write head and the magnetic recording layer, ideally by providing a flatter, smoother, and thinner protective coating which maintained or even enhanced the durability of the total recording media structure. It would also be advantageous to provide alternative methods and systems for depositing such protective layers, for use in the production of magnetic recording media, as well as integrated circuits, optics, machine tools, and a wide variety of additional industrial applications.

2 Description of the Background Art

U.S. Pat. No. 5,182,132 describes magnetic recording media having a diamond-like carbon film deposited with alternating circuit plasma enhanced chemical vapor deposition methods. U.S. Pat. No. 5,462,784 describes a fluorinated diamond-like carbon protective coating for magnetic recording media devices. European Patent Application 700,033 describes a side-mounted thin film magnetic head having a protective layer of diamond-like carbon. European Patent Application No. 595,564 describes a magnetic recording media having a diamond-like protective film which consists of carbon and hydrogen.

U.S. Pat. No. 5,156,703 describes a method for the surface treatment of semiconductors by particle bombardment, the method making use of a capacitively coupled extraction grid to produce an electrically neutral stream of plasma. V. S. Veerasamy et al. described the properties of tetrahedral amorphous carbon deposited with a filtered cathodic vacuum arc in *Solid-State Electronics*, vol. 37, pp. 319–326 (1994). The recent progress in filtered vacuum arc deposition was reviewed by R. L. Boxman in a paper presented at the International Conference of Metallurgical Coatings and Thin Films located at San Diego in April of 1996. Electron cyclotron wave resonances in low pressure plasmas with a superimposed static magnetic field were described by Professor Oechsner in *Plasma Physics*, vol. 15, pp. 835–844 (1974).

SUMMARY OF THE INVENTION

The present invention provides systems and methods for the deposition of an improved diamond-like carbon material particularly for the production of magnetic recording media. The diamond-like carbon material of the present invention is highly tetrahedral, that is, it features a large number of the sp^3 carbon—carbon bonds which are found within a diamond crystal lattice. The material is also amorphous, providing a combination of short-range order with long-range disorder, and can be deposited as films which are ultrasmooth and continuous (pin-hole free) at thicknesses substantially lower than known amorphous carbon coating materials. The carbon protective coatings of the present invention will often be hydrogenated, generally providing a significantly higher percentage of carbon—carbon sp^3 bonds than known hydrogenated amorphous diamond-like carbon coatings having similar compositions, and may optionally be nitrogenated. In a preferred method for depositing of these materials, capacitive coupling forms a highly uniform selectively energized stream of ions from a dense, inductively ionized plasma. Such inductive ionization is enhanced by a relatively slow moving (or "quasi-static") magnetic field which promotes resonant ionization and ion beam homogenization. Clearly, the materials, systems, and methods of the present invention will find applications not only in the field of magnetic recording media and related devices, but also in integrated circuit fabrication, optics, machine tool coatings, and a wide variety of film deposition and etching applications.

In a first aspect, the present invention provides a method for producing magnetic recording media, the method comprising forming a magnetic layer over a substrate, and ionizing a source material so as to form a plasma containing carbon ions. The carbon ions are energized to form a stream from the plasma toward the substrate, so that carbon from the ions is deposited on the substrate. The ions impact with an energy which promotes formation of sp^3 carbon—carbon bonds. Advantageously, such a method can form a highly tetrahedral amorphous carbon protective layer, generally having more than about 15% sp^3 carbon—carbon bonds. Generally, the impact energy of the energetic carbon ions is within a pre-determined range to promote formation of the desired lattice structure, the bonds apparently being formed at least in part by subplantation. Preferably, each carbon ion impacts with an energy of between about 100 and 120 eV. In many embodiments, the resulting highly tetrahedral amorphous carbon protective layer includes more than about 35% sp^3 carbon—carbon bonds, with particularly preferred methods producing more than about 70% sp^3 carbon—carbon bonds.

Generally, the stream will be primarily composed of ions having a uniform weight, and the impact energy will preferably be substantially uniform. In some embodiments, this uniformity is promoted through filtering of the ion stream. In such cases, the energizing step generally comprises striking a plasma using a solid cathodic arc of carbon source material. Alternatively, the stream will be energized by applying an alternating potential between a coupling electrode and an extraction grid so as to self-bias the plasma relative to the extraction grid through capacitive coupling, thereby extracting the ion stream through the grid. Hydrogen and/or nitrogen may also be included, both in the ion stream and the protective layer.

In another aspect, the present invention provides magnetic recording media comprising a substrate, a magnetic layer disposed over the substrate, and a protective layer disposed over the magnetic layer. The protective layer comprises a highly tetrahedral amorphous carbon, generally having more than about 15% sp^3 carbon—carbon bonds. Preferably, these bonds are formed at least in part by directing an energetic stream of carbon ions onto the substrate. In many embodiments, the protective layer includes more than about 35% sp^3 carbon—carbon bonds, with particularly preferred embodiments including more than about 70% sp^3 carbon—carbon bonds. Such protective layers are ultrasmooth and continuous at thicknesses of less than about 75 Å, and will provide durable recording media even at thicknesses of less than about 50 Å. Furthermore, the hardness and tribological performance of these dense protective materials may allow highly durable recording media with areal recording densities of over 1 gigabyte per square inch with reduced read/write head glide heights of lower than about 1 μ", optionally within a near-contact or continuous contact recording systems.

In another aspect, the present invention provides a method for enhancing an ion beam, the ion beam produced by confining a plasma within a plasma volume, inductively ionizing the plasma, and forming a stream of ions from within the plasma volume by capacitive coupling. The method comprises moving a magnetic field through the plasma to promote resonant inductive ionization, preferably by sequentially energizing each of a plurality of coils disposed radially about the plasma volume.

In another aspect, the present invention provides an inductive ionization system for use with an ion-beam source. The source includes an antenna disposed about a plasma volume for inductively ionizing a plasma therein. A coupling electrode is exposed to the plasma volume and an extraction electrode is disposed over an opening of the plasma volume, so that the extraction electrode is capable of expelling ions of the plasma through the grid by capacitive coupling. The system comprises at least one coil disposed adjacent the plasma volume capable of applying a transverse magnetic field to the plasma volume so as to promote resonant inductive ionization by the antenna. The magnetic field can

be moved through the plasma container to homogenize the expelled ion stream. This movement of the magnetic field, which is optionally provided by selectively energizing coils radially disposed about the plasma volume, may also further densify the plasma by promoting particle collisions through a churning or mixing effect.

In another aspect, the present invention provides a diamond-like material comprising carbon in the range between about 72 and 92 atomic percent and hydrogen in the range between about 8 and 18 atomic percent. The material is amorphous, and between about 15 and 85 percent of carbon—carbon bonds are sp^3 bonds. Generally, sp^3 bond formation will be promoted with subplantation using ion-beam deposition from a plasma beam source, so that the number of such bonds will be higher than known materials having similar compositions. Hence, the highly tetrahedral amorphous carbon and hydrogenated carbon of the present invention will have fewer polymer-like hydrogen chains, and will generally exhibit enhanced thermal and mechanical stability.

In another aspect, the present invention provides a method for deposition of highly tetrahedral amorphous carbon over a substrate, the method comprising ionizing a source material to form a plasma and confining the plasma within a plasma volume. The plasma is capacitively coupled to form a stream flowing outwardly from within the plasma volume. The stream includes carbon ions from the plasma and is directed onto the substrate. Advantageously, such a method allows deposition of carbon ions of uniform size with a uniform energy, and allows tailoring of the energetic carbon ions to specifically promote sp^3 bonding through subplantation. The source material typically comprises a gas having a substantially coherent dissociation energy spectra, the source gas ideally comprising acetylene. Preferably, the ions strike the substrate with an impact energy of between about 57 and 130 eV for each carbon atom, ideally being between about 80 and 120 eV each.

In another aspect, the present invention provides an ion-beam source comprising a container defining a plasma confinement volume. The container has an opening, and an antenna is disposed about the plasma volume so that application of a first alternating potential to the antenna is capable of inductively ionizing a plasma therein. A coupling electrode is electrically coupled to the plasma volume, and an extraction electrode is disposed over the opening of the container. The extraction electrode has a surface area which is substantially less than the coupling electrode surface, so that application of a second alternating potential between the coupling electrode and the extraction electrode is capable of expelling ions of the plasma through the grid. Preferably, at least one coil is disposed adjacent the container, and is capable of applying a transverse magnetic field to the plasma volume, thereby promoting highly efficient inductive ionization resonance by the antenna. Ideally, the magnetic field can be moved through the plasma container to homogenize the expelled ion stream. This movement of the magnetic field, which is optionally provided by selectively energizing coils radially disposed about the plasma confinement volume, may further densify the plasma by promoting particle collisions with a churning or mixing effect.

In yet another aspect, the present invention provides an ion-beam source comprising plasma containment means for confining a plasma within a plasma volume. Inductive ionization means inductively couples a first alternating current with the plasma so as to ionize the plasma within the plasma volume. A moving magnetic field generation means provides resonant densification and homogenization of the ionized plasma within the plasma volume. Ion extraction means forms a stream of ions out from the plasma volume.

In another aspect, the present invention provides a method for producing an ion beam, the method comprising confining a plasma within a plasma volume, inductively ionizing the plasma and forming a stream of ions from within the plasma volume by capacitively coupling the plasma with an extraction grid. This capacitive coupling self-biases the plasma relative to the grid, and can be used to produce a quasi-neutral plasma stream. Generally, a transverse magnetic field is applied to densify the plasma by promoting resonant inductive ionization. Ideally, the magnetic field is moved through the plasma volume to homogenize the plasma and plasma stream.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a cross-sectional view of a magnetic recording disk including the tetrahedral amorphous hydrogenated carbon protective layer of the present invention.

FIGS. 1A and B illustrate the effects of nitrogen doping on the tetrahedral amorphous hydrogenated carbon of the present invention.

FIG. **2** schematically illustrates a method for depositing the highly tetrahedral amorphous hydrogenated carbon over the disk of FIG. **1**, and also shows a hybrid inductive, capacitive plasma beam source according to the principles of the present invention.

FIG. 2A is a cross-sectional view of the hybrid source of FIG. **2**, showing the inductive ionization antenna and quasi-static magnetic field generating coils which densify and homogenize the plasma.

FIG. 3A illustrates an alternative method and system for depositing highly tetrahedral amorphous hydrogenated carbon over the disk of FIG. **1** using an acetylene plasma from a plasma beam source.

FIGS. 3B and C illustrate capacitive coupling of the plasma to extract a stream of ions when using the plasma beam source of FIG. 3A.

FIG. 3D illustrates an alternative embodiment of a plasma beam source, in which the effective area of the coupling electrode can be varied to provide further control over the ion density and ion energy.

FIGS. 3E and F illustrate operating characteristics of plasma beam sources for deposition of diamond-like carbon.

FIGS. 4A and B illustrate known resonant inductive ionization of a plasma with a fixed magnetic field.

FIGS. 4C and D explain densification of the plasma provided by Electron Cyclotron Wave Resonance.

FIG. **5** illustrates an alternative method and deposition system for producing the recording disk of FIG. **1**, which system relies upon a filtered cathodic arc for deposition of the highly tetrahedral amorphous hydrogenated carbon material of the present invention.

FIGS. **6A–8** show experimental data, as described in detail in the experimental section.

DESCRIPTION OF THE SPECIFIC EMBODIMENTS

Referring now to FIG. **1**, a rigid magnetic recording disk **2** comprises a non-magnetic disk substrate **10**, typically composed of an aluminum alloy, glass, ceramic, a glass-ceramic composite, carbon, carbon-ceramic composite, or the like. An amorphous nickel-phosphorus (Ni—P) layer **12** is formed over each surface of the disk substrate **10**, typi-

cally by plating. The Ni—P layer is hard, and imparts rigidity to the aluminum alloy substrate. A chromium ground layer **14** is formed over Ni—P layer **12** typically by sputtering, and a magnetic layer **16** is formed over the ground layer **14**. Please note that these layers are shown schematically only, as NiP layer **12** will typically be much thicker than the other layers.

The magnetic layer **16** comprises a thin film of a ferromagnetic material, such as a magnetic oxide or magnetic alloy. Magnetic layer **16** is typically sputtered over ground layer **14** in a conventional manner. The magnetic layer will often be composed of a cobalt alloy, such as a CoCrTaPtB, CoCrPtB, CoCrTa, CoPtCr, CoNiCr, CoCrTaXY (X and Y being selected from Pt, Ni, W, B, or other elements) or the like. The magnetic layer may be formed as a single layer, or may comprise two or more layers formed over one another. The thickness of magnetic layer **16** is typically in the range from about 200 Å to 800 Å.

Of particular importance to the present invention is a protective layer **18** which is formed over the magnetic layer. The protective layer **18** of the present invention will generally comprise a highly tetrahedral amorphous carbon, typically having more than about 15% sp^3 carbon—carbon bonds, preferably being more than about 35% sp^3 carbon—carbon bonds, and ideally being over about 70% sp^3 carbon—carbon bonds, as measured using Raman fingerprinting and electron energy loss spectroscopy. Along with carbon, protective layer **18** may also include hydrogen, generally forming in the range between about 2 and 30 atomic percent of the protective material, preferably being between 8 and 18 atomic percent. A conventional lubricating layer **20** is disposed over the protective layer.

Although hydrogen is known to increase the percentage of sp^3 bonding of diamond-like carbon produced by known chemical vapor deposition processes, protective layer **18** will generally include significantly less hydrogen than comparable known diamond-like films. This compositional difference may be explained in part by the formation of sp^3 bonds through subplantation of the energetic carbon ions during deposition. Effectively, the energetic ions deposited using the methods described hereinbelow impact on the growing film surface, and are driven into the film so as to cause densification. This process may also explain why the protective layer of the present invention includes a higher percentage of quarternary carbon sites (sp^3 carbon sites with no hydrogen neighbors) and greater hardness than known alternative amorphous carbon materials.

The microstructure of conventional hydrogenated amorphous carbons includes polymer-like hydrocarbon chains. Although hydrogen enhances the formation of tetrahedrally bonded carbon atoms above a certain threshold value of hydrogen content, carbon films become polymeric and hence lose their protective properties. Through subplantation, the materials of the present invention overcome this limitation. As subplantation promotes formation of sp^3 bonds without relying on additional hydrogen content alone, polymerization can be avoided. This represents a substantial advantage over known, more highly hydrogenated diamond-like carbon materials, in which polymerization significantly limits both thermal and mechanical stability. In contrast, the carbon—carbon sp^3 bonds of the materials of the present invention will generally be stable up to temperatures of about 700° C., so that an enhanced percentage of sp^3 bonds with a low hydrogen content represents a significant advantage.

Optionally, the films of the present invention may also be nitrogenated. In contrast to known hydrogenated carbon, the electrical conductivity of the present highly tetrahedral amorphous carbon can be controllably varied over a wide range by the selective incorporation of nitrogen during the C_2H_2 plasma beam deposition process described hereinbelow. Advantageously, this variation will be provided without significantly varying the structural properties of the film. With conventional hydrogenated carbon, nitrogen incorporation may be related to the formation of sp^2 bonds. This will be evident by variations in the mechanical and optical properties of the films deposited, for which hardness and optical gap will decrease with nitrogen content. With the present film materials and deposition methods, a classic doping effect is observed, in which electrical conductivity can be controllably varied by as much as 5 orders of magnitude or more, as is shown in FIGS. **1**A and B. Doping can be provided by varying nitrogen pressure within a plasma volume of an acetylene fed plasma beam source, typically to provide films having from about 4 to about 30 atomic percent nitrogen. This doping effect of highly tetrahedral amorphous carbon and hydrogenated carbon will find particular application for the fabrication of integrated circuits and the like.

The highly tetrahedral amorphous carbon materials of the present invention also provide a number of advantages over known protective layers for recording media. The bond structure of this material provides physical properties approaching those of diamond, including a hardness of over about 50 GPa, with certain species having hardness of up to about 80 GPa. Furthermore, the present protective overcoats have high density, generally being over about 2.5 grams per cubic centimeter, and are also very chemically inert.

Of particular importance to recording media, these coatings are smooth and continuous (pinhole-free) at very low thicknesses, and provide a durable protective layer when deposited to a thickness of less than 75 Å, preferably being less than 50 Å thick. In fact, films of over 150 Å may be more susceptible to delamination, and surface roughness may increase with thickness. The high mechanical hardness and low friction surfaces provided by these materials lead to enhanced tribological performance, providing recording media which are highly tolerant to the mechanical abrasion and contact start-stop demands of modern recording media systems, and allowing increased areal density through reduced separation between the read/write and the magnetic layer. This separation may be reduced by either a reduction in the protective layer thickness, or by a reduction in head glide height, and preferably by a reduction in both. Protective layer **18** is generally in the range between about 30 Å and 70 Å, which will allow the disk to meet recording media industry durability and stiction test requirements.

The composition and characterization of the protective film of the present invention are highly dependent on the deposition method, and in particular, depend strongly on the energy and uniformity of carbon ions striking the deposition surface.

An exemplary system and method for depositing protective layer **18** on rigid recording disk **2** will be described with reference to FIGS. **2** and **2**A. Hybrid ion beam source **30** generally includes an inductive ionization system **32**, a quasi-static magnetic field system **34** and a capacitive ion beam extraction system **36**.

In general terms, induction system **32** ionizes a plasma **38**. The energy transfer between induction system **32** and plasma **38** is greatly enhanced and homogenized by a transverse magnetic field generated by quasi-static field system **34**. The deposition ions of plasma **38** are spatially

directed to recording disk **2** for to any other substrate on which deposition is desired or from which etching will be performed) using capacitive coupling system **36**

Although hybrid source **30** provides a particularly advantageous system for deposition of the protective coating **18** a variety of alternative deposition systems may also be used As a plasma beam source deposition system shares a number of the features of hybrid source **30**, but is simpler in operation diamond-like carbon deposition using a plasma beam source **50** will be described with reference to FIGS **3A–F**, after which other aspects of hybrid source **30** will be explained in more detail

Referring now to FIG **3A**, the use of plasma beam source **50** for the deposition of carbon will generally be described with reference to depositing protective layer **18** on magnetic recording media **2** As has been mentioned above, these carbon deposition systems and methods will have a wide variety of alternative uses, particularly in the areas of integrated circuits fabrication optics and machine tools

Plasma beam source **50** includes a plasma container **52** which defines a plasma volume **54** therein Container **52** is typically an 8 cm diameter glass tube, or may alternatively comprise quartz or the like A coupling electrode **56** having a relatively large surface **58** here forms one end of the container Alternatively, the coupling electrode may be disposed within or external to the container and may optionally extend axially along the walls of the container Regardless, coupling electrode **56** is generally electrically coupled to the plasma to a matching network **60**, and to a radiofrequency coupling power supply **62**. Plasma coupling system **36** includes coupling electrode **56**, the frequency generator and matching network **60**, **62** and an extraction grid **64** Typically the extraction grid will be grounded as shown

As is explained more fully in U.S Pat No 5,156,703, the full disclosure of which is herein incorporated by reference, extraction grid **64** has a much smaller surface area exposed to the plasma than the coupling electrode **56** In operation, RF power typically at about 13 56 MHz is supplied by the frequency generator through the matching network and a capacitor to the coupling electrode This frequency will often be set by government regulations, and may alternatively be about 27 12 MHz or some other multiple thereof The extraction grid typically comprises a graphite rim **66** defining an aperture and tungsten filaments which are maintained under tension Hence extraction grid **64** resists any distortion due to thermal expansion A number of alternative materials may be used in the filaments, the filament materials preferably having a low sputtering yield

Generally internal pressure within plasma volume **54** is reduced by removing gas through vacuum port **68** While the vacuum port is here shown behind the grid, it will preferably be disposed between grid **64** and disk **2** Advantageously, when a plasma is struck between the coupling electrode and the extraction grid the plasma shifts to a positive DC potential with respect to the extraction grid, due to the relative mobility of the electrons as compared to the ions within the plasma Specifically, the greater mobility of electrons than ions in the plasma causes the plasma to form a sheath between itself and each electrode The sheaths act as diodes, so that the plasma acquires a positive DC bias with respect to each electrode

The total radiofrequency potential V_0 will be divided between the sheaths adjacent the powered electrode and the grounded electrode, according to their respective capacitances. As the extraction electrode is grounded, the voltage of the plasma itself is given by the equation

$$V=V_0(C_c/(C_g+C_c))$$

wherein C_c is the capacitance of the coupling electrode, while C_g is the capacitance of the extraction grid.

Where the extraction electrode is grounded, this plasma voltage biases the plasma relative to the grid, accelerating the ions through the extraction grid and toward the substrate As can be determined from the above equation, the plasma beam source allows the biasing voltage to be selectively controlled, providing a highly advantageous mechanism for controlling ion impact energy

As capacitance varies inversely with area, the size of the bias voltage at each electrode can be controlled by varying the electrode areas As the extraction grid has a much smaller area than the coupling electrode, the biasing of the plasma relative to the coupling electrode is relatively low, so that source **50** provides a fairly efficient use of the source gas material which is generally provided through source inlet **70** adjacent coupling electrode **56** While some material will be deposited on the container walls at higher power settings, use of the plasma beam source in an etching mode may allow self cleaning

The relationship of electron current, ion current, and the radiofrequency potential is illustrated in FIG **3B** A simplified electrical diagram for analysis of the plasma, the extraction grid sheath, and the coupling grid sheath, is shown in FIG **3C**

A still further aspect of the plasma beam source carbon deposition system and method of the present invention is illustrated in FIG **3D** Plasma **74** is here contained within a hyperbolic magnetic field produced by magnets **78**. An axially movable coupling electrode **80** is supported by a movable ceramic pipe **82** which slides axially through a ceramic end **84** of the plasma container vessel

The magnetic confinement of the plasma allows the effective area of coupling electrode **80** to be varied by moving the coupling electrode axially relative to the plasma This allows the bias voltage (and hence the ion energy) to be varied without changing the radiofrequency power or the gas pressure Alternatively, the ion saturation current density (deposition rate) and ion energy can be varied by changing the radiofrequency power and gas feed stock flow rate The ion current and ion energy distribution can be measured with a Faraday cup **86** in the substrate plane **88** FIG **3E** shows variations of ion current and mean ion energy with electrode position D for a range of radiofrequency powers

The ion energy depends on at least two factors: the acceleration potential across the grid sheath, and the energy lost by collisions within the sheath The effects of these factors are illustrated in FIG **3F**

The inset to FIG **3F** shows that the ion energy distribution of the plasma beam is quite sharp, with a width of approximately 5% about the bias voltage The sharpness apparently arises for at least two reasons. First, ions lose little energy in the low plasma pressure through collisions within the sheath Second, the sheath width varies inversely with the square root of pressure, so that the sheath is quite wide at low pressures. Where the ion transit time across the sheath is longer than the radiofrequency period, the ions may be accelerated by the mean voltage rather than the instantaneous voltage. The ion energy distribution width is also found to vary linearly with pressure, which indicates that the ion energy distribution width is controlled mainly by ion collisions in and above the sheath

The decomposition or dissociation of hydrocarbons in plasma **74** depends strongly on the source gas, the operation pressure, and the gas flow rate. Usually, hydrocarbon plasmas exhibit a wide spectrum of hydrocarbon radicals in an